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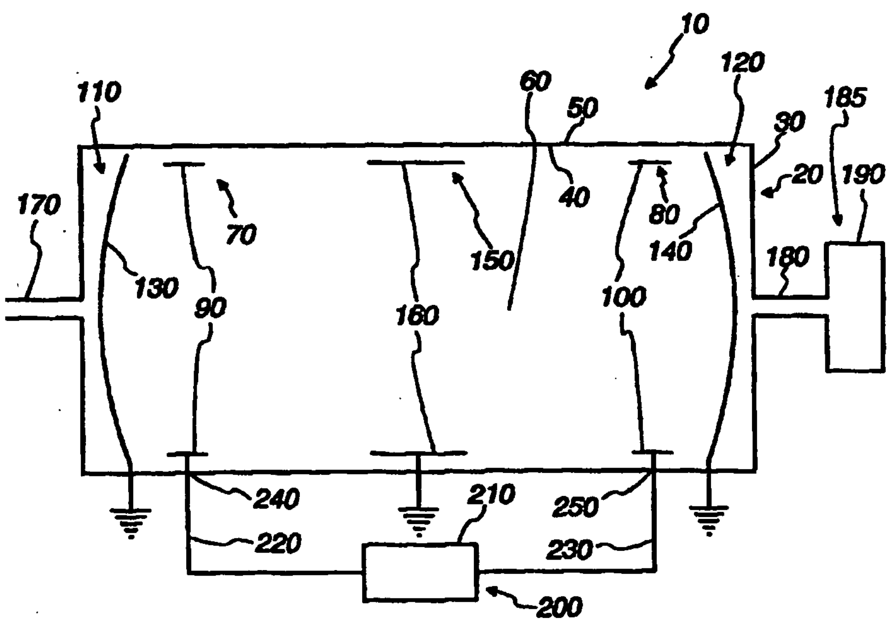
(57) Abstract

An electrostatic accelerated-recirculating fusion neutron/proton source is disclosed. The energetic neutron/proton source comprises an axially elongated hollow vacuum chamber having an inner and outer wall. Reflectors are located at opposite ends of the vacuum chamber so that their centers lie on the axis of the vacuum chamber. A cathode that is 100 % transparent to oscillating particles is located within the vacuum chamber between the reflectors, defining a central volume and having the same axis as the vacuum chamber. Anodes that are 100 % transparent to oscillating particles are located near opposite ends of the vaccum chamber between the reflectors dishes and the cathode, having axes coincident with the axis of the vacuum chamber. A means is also provided for introducing controlled amounts of reactive gas into the vacuum chamber, and its central volume. Further, a means is provided for applying an electric potential between said anodes and said cathode and said reflectors to produce from the reactive gas ions within the central volume and to cause the recirculation of ions and electrons within the vacuum chamber, thus reducing the loss of particles. In an alternative embodiment, a means for generating a magnetic field in the axial direction is attached to the circumference of the vacuum chamber.



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ELECTROSTATIC ACCELERATED-RECIRCULATING FUSION NEUTRON/PROTON SOURCE

Background of the Invention

Field of the Invention

This invention relates to a particle generator and, more particularly, to an electrostatic accelerated-recirculating fusion neutron/proton source ("neutron/proton source") that confines controlled nuclear fusion reactions inside a negative potential well structure.

Description of the Prior Art

Experimental work has been done on inertial-electrostatic confinement ("IEC") devices. These devices generate energetic particles (i.e. ions and electrons) and contain them within an electrostatic field. One such experimental study employed ion-gun injectors that demonstrated the ability to generate approximately 10^9 D-T neutrons per second at maximum currents and voltages. These maximums were established by grid-cooling requirements and voltage breakdown limits. The ion guns employed special characteristics that are disclosed in U.S. Patent 3,448,315 issued to R.L. Hirsch et al. The '315 patent discloses an improvement for forming and directing a beam of ions from a chamber with increased efficiency.

U.S. Patent 3,386,883 issued to P.T. Farnsworth discloses ion guns mounted around a spherical anode that surrounds a spherical cathode. Ions from the guns are focused into the center of the cathode. U.S. Patent 3,258,402, also issued to P.T. Farnsworth, is an earlier version of the same device that discloses a spherical cathode surrounding a spherical anode. This patent suggests that with a proper choice of materials for the cathode, the central gas may be ionized by electron emission from the cathode, thus eliminating the need for ion guns.

U.S. Patent 3,530,497 issued to Hirsch et al., also illustrates a spherical anode, a concentrically positioned ion-source grid, and a cathode, which is spherical and is permeable to charged particle flow. However, both the spherical cathode and the ion-source grid are required and the ion-source grid is placed between the cathode and the anode. Varying

potentials are applied to each of the three electrodes, thus establishing a first electric field in the space between the anode and the ion-source grid, and a second electric field in the space between the ion-source grid and the cathode, which is at a different potential than the first electric field. Ions formed inside the ion-source grid are propelled toward the centrally located cathode due to the potential difference. These ions are focused toward the center of the inside of the cathode where they interact, thereby producing a fusion reaction.

One disadvantage of this device is that it requires an ion-source grid in addition to the spherical cathode and anode. Furthermore, a thermionic cathode is required in the space between the outer anode and the ion-source grid, such that electrons from the thermionic cathode will flow toward the grid rather than to the outer anode. With the addition of each element, the complexity and cost of the apparatus increases.

The inventors named here participated in preparing papers entitled "Advantages of Inertial-Electrostatic Confinement Fusion," published in Fusion Technology, Vol. 20, p. 850, December 1991 and "Characterization of an Inertial-Electrostatic Confinement Glow Discharge (IECGD) Neutron Generator," published in Fusion Technology, Vol. 21, p. 1639, May 1992. These papers reported studies of devices partly developed from information in the patents of Hirsch and Farnsworth.

Problems with the prior art IEC devices include that they are expensive to manufacture, are bulky, and require precise alignment of components, such as ion guns, in order to operate properly. With these complications, their use was intended for higher-intensity applications, viewed as leading to a fusion energy source, which implies neutron emission rates above 10^{14} neutrons per second ("n/s"). Other applications, such as neutron activation analysis, require a compact lower-intensity source (i.e. about 10^6 n/s), which is typically met using radioisotope neutron sources, e.g. Cf-252. However, disadvantages of

such radioisotopes include their relatively short half lives and the broad energy spectrum of their emitted neutrons. Another problem with the radioisotope design is that it does not have an on/off capability. Thus, the source must be stored in bulky protective shielding when not in use. Further, Cf-252 must be produced using a high-flux fission reactor, making it expensive and, due to a reduction in such reactors operating in the U.S. in recent years, fairly scarce. Thus, there is a strong motivation to seek other types of neutron sources.

In addition to neutrons, some applications, such as proton emission isotope production, require a high energy proton source. The proton source most commonly used today is a large and expensive proton accelerator. Such devices could easily be replaced by a simpler, more compact IEC of the present invention using D-^{3}He reactions to produce 14 MeV protons.

Another device for containing electrons is disclosed in U.S. Patent No. 4,788,024 to Maglich et al. This device comprises two circular molybdenum meshes or grids, which are 90% transparent to charged particles. A negative DC voltage is placed at each plate, thereby containing the electrons in the space between the grids and causing the ions to oscillate within the grids. However, the device is not 100% transparent to oscillating electrons. Thus, electrons are lost to the grid structure, reducing the effectiveness of the overall device.

Another alternate low-intensity neutron source uses a miniature deuteron accelerator to bombard a solid target coated with tritium. (R.C. Smith, et al., <u>IEEE Trans. on Nuc. Sci.</u>, <u>35</u>, 1, 859 [1988]). Currently available small (i.e. 10^6 - 10^8 n/s) neutron generators of this type use a titanium target coated with deuterium or a deuterium-tritium mixture. The device typically operates in a short-pulse mode with a moderate repetition rate in order to avoid overheating of the target. Versions of this concept with higher neutron intensities have been

built using a high-speed rotating target to prevent overheating, but these devices are very expensive.

These generators have many disadvantages. For instance, they do not operate very long before maintenance becomes necessary. Because they use tritiated targets, the user must comply with radioisotope-handling regulations. Furthermore, the target's effectiveness typically decreases with time due to the desorption of tritium during direct bombardment by high energy ions. The target is ultimately exhausted and must be replaced, at great expense, after only several hundred hours of operation. Also, the decay of tritium leads to build-up of ^3He gas pressure. Moreover, the internal surface of the generator eventually becomes contaminated by titanium particles that sputter off the target due to ion bombardment. This contamination reduces the effective insulation of the walls of the device, leading to arcing. This type of generator also has the storage and disposal problems associated with radioisotope sources.

The present invention is intended to overcome the disadvantages of these various low-intensity neutron/proton sources.

Summary of the Invention

According to the present invention, an electrostatic accelerated-recirculating fusion neutron/proton source is provided, comprising and axially elongated hollow vacuum chamber having an inner and outer wall. Reflectors are located at opposite ends of the vacuum chamber so that their centers lie on the axis of the vacuum chamber. A cathode that is 100% transparent to oscillating particles is located within the vacuum chamber between the reflectors, defining a central volume and having the same axis as the vacuum chamber. Anodes that are 100% transparent to oscillating particles are located near opposite ends of the vacuum chamber between the reflectors and the cathode, having axes coincident with the axis

of the vacuum chamber. A means is also provided for introducing controlled amounts of reactive gas into the vacuum chamber, and its central volume. Further, a means is provided for applying an electric potential between said anodes and said cathode and said reflectors dishes to produce ions from the reactive gas within the central volume and to cause the recirculation of ions and electrons within the vacuum chamber, thus reducing the loss of particles. In an alternative embodiment, a means for generating a magnetic field in the axial direction is attached to the circumference of the vacuum chamber.

Objects of the Invention

It is an object to provide a neutron/proton source that can be switched on or off.

Another object is to provide a neutron/proton source with a cathode that is 100% transparent to oscillating ions, thereby allowing high ion recirculation and eliminating ion-cathode collisions, which reduces ion losses and overheating and erosion of the cathode.

Another object is to provide a neutron/proton source that is simple in its operation and construction, sturdy in its design and is a low-cost fusion neutron/proton source.

Another object is to provide a neutron/proton source that is easily portable.

Another object is to provide a neutron/proton source that does not use a radioisotope neutron source.

It is another object to provide a neutron/proton source that does not use an accelerator-solid target design.

It is still another object to provide a neutron/proton source that does not use a spherical design, thereby allowing for specialized applications of the neutron/proton source where an alternative geometry is of interest.

Another object is to provide a neutron/proton source with two anodes and two reflectors that create positive potential wells, which allow electrons to oscillate within the potential wells, thereby reducing ion loss rate.

Another object is to provide a neutron/proton source with two anodes that are 100% transparent to oscillating particles, thereby allowing high particle recirculation and eliminating particle-anode collisions, which reduces particle losses and overheating and erosion of the anodes.

Another object of the invention is to provide a neutron/proton source with good recirculatory ion beam focusing due to an electron microchannelling effect caused by hollow cylindrical anodes.

It is another object to provide a neutron/proton source with nearly isotropic angular distribution emitted along ion microchannels, to a first approximation approaching an isotropic line source or point source, depending on the length of the cathode.

Another object of the invention is to provide a neutron/proton source that produces a plurality of dense ion beams, thereby causing a greater number of particle collisions.

It is an object of the invention to provide an apparatus for generating a fusion reaction resulting in a neutron/proton source with a neutron generation rate proportional to the square or higher power of the total recirculation ion-beam current.

Another object of the invention is to achieve improved power efficiency by using a pulsed power supply, thereby providing an improved neutron yield per time averaged input power due to the current squared (or higher power) scaling of neutron yield.

It is an object of the invention to provide an apparatus that can produce 2.5 MeV neutrons from D-D reactions using deuterium gas and easily can be converted to produce 14 MeV neutrons from D-T reactions by using a mixture of deuterium and tritium gas ("D-T").

It is an object of the invention to provide an apparatus that easily can be converted from producing neutrons to producing energetic protons by changing the gas from deuterium or a deuterium, tritium mixture, to a mixture of deuterium and Helium-3 ("D-^{3}He").

Still another object of the invention is to provide a neutron/proton source with a magnetic field that confines particles in the radial direction, thereby reducing further the particle loss rate.

Other objects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings. Throughout the drawings, like reference numerals refer to like parts.

Brief Description of the Drawings

Fig. 1 is a diagrammatic illustration of the neutron/proton source embodying the present invention.

Fig. 2 is a diagram of the idealized negative and positive electric potential wells generated by the cylindrical cathode, cylindrical anodes and reflecting dishes.

Fig. 3 is a diagrammatic illustration of an alternate embodiment of the neutron/proton source having a plurality of magnetic rings.

Description of the Preferred Embodiment

While the invention will be described in connection with a preferred embodiment, it will be understood that it is not intended to limit the invention to this embodiment. On the contrary, it is intended to cover all alternatives, modifications and equivalents as may be included within the spirit and scope of the invention.

Turning first to Figs. 1 and 2 the portable electrostatic accelerated-recirculating fusion neutron/proton source 10 of the present invention first comprises a hollow vacuum chamber 20. In the preferred embodiment, the hollow vacuum chamber 20 is a cylindrical vacuum chamber 30 having an inner wall 40 and an outer wall 50, and defining a central volume 60. The cylindrical vacuum chamber 30 is preferably made from an electrical insulator such as glass. However, other electrical insulators, such as ceramics or metal oxides, may be used without departing from the present invention. The dimensions of the test model cylindrical vacuum chamber 30 are 10 cm in diameter and 61 cm long. However, other dimensions may be used without departing from the present invention.

X-rays are generated during the operation of the neutron/proton source 10 from Brensteshlung emission and by stray electrons striking metallic parts of the device. Because glass does not attenuate x-rays well, added lead shielding should be used to provide x-ray attenuation. However, only a thin layer of lead is necessary because X-rays are easily

attenuated. X-ray attenuation can also be provided by any high-z material, such as ceramic, or by using leaded glass to make the cylindrical vacuum chamber 30.

Two anodes that are 100% transparent to oscillating particles 70 and 80 are located at either end of the cylindrical vacuum chamber 30 having axes coincident with the axis of the cylindrical vacuum chamber 30. In the preferred embodiment, the two anodes 70 and 80 are substantially cylindrical and hollow anodes 90 and 100. In the test model, the cylindrical anodes 90 and 100 are 9 cm in diameter. However, another diameter may be used without departing from the present invention.

Reflectors 110 and 120 are located at either end of the cylindrical vacuum chamber 30 between the cylindrical anodes 90 and 100 and the ends of the cylindrical vacuum chamber 30, so that their centers lie on the axis of the cylindrical vacuum chamber 30. In the preferred embodiment, the reflectors 110 and 120 are concave reflecting dishes 130 and 140 whose concave surfaces face the center of the cylindrical vacuum chamber 30. The concave reflecting dishes 130 and 140 are electrically grounded. The focal length of the concave reflecting dishes 130 and 140 is set to obtain good electron microchannel formulation, i.e. approximately the distance to the mouth of the cathode.

In accordance with one aspect of the invention, and as seen in Fig. 2, this anode configuration allows electrons to oscillate inside a positive electric potential created by the cylindrical anodes 90 and 100 and the concave reflecting dishes 130 and 140, rather than being lost after ionization. This design serves six functions: (1) because the cylindrical anodes 90 and 100 are cylinders and their ends are uncovered, they are 100% transparent to oscillating particles (i.e. ions and electrons), and consequently particle losses due to collisions of particles with the inner wall 40 of the cylindrical vacuum chamber 30 are reduced, thereby reducing overheating and erosion of the cylindrical anodes 30 and 40 due to direct particle-

anode collisions, and allowing for better electron beam confinement, (2) it produces a more energy efficient system because the electrons have more opportunity to ionize neutral atoms, thereby creating more electron-ion pairs, (3) because the system is more energy efficient, the device may be operated at a lower pressure, which may help to reduce collisional loss, (4) the design causes an electron microchannelling effect, which in turn focuses ions into the microchannels, thereby creating good recirculating ion beam focusing, (5) the reduced loss of electrons leads to better charge balance in the system, which leads to better ion beam confinement, and (6) due to the high ion density in the ion beams, fusion reactions are enhanced.

In the test model, both the cylindrical anodes 90 and 100 and the concave reflecting dishes 130 and 140 are made of stainless steel. However, any material that can sustain a high temperature without much sputtering may be used. Tungsten has been found to be a good material, but it is expensive.

A cathode that is 100% transparent to oscillating particles 150 is centered in the middle of the cylindrical vacuum chamber 30 having the same axis as the cylindrical vacuum chamber 30 and the cylindrical anodes 90 and 100. In the preferred embodiment, the cathode 150 is a substantially cylindrical and hollow cathode 160, with a body that is solid throughout. In the test model, the cylindrical cathode 160 is made of stainless steel, and is 10 cm long and 9 cm in internal diameter. However, any material that can sustain a high temperature without much sputtering, such as Tungsten, and any other dimensions may be used without departing from the present invention. The cylindrical cathode 160 is electrically grounded. The role of the cylindrical cathode 160 is twofold. First, it is used to accelerate ions. Second, because the cylindrical cathode 160 is a cylinder and its ends are uncovered, it is 100% transparent to oscillating ions. This result reduces ion losses due to collisions of ions with the inner wall 40 of the cylindrical vacuum chamber 30, thereby reducing

overheating and erosion of the cylindrical cathode 160 due to direct ion-cathode collisions, and allowing for better ion beam confinement.

A reactive gas is supplied to the cylindrical vacuum chamber 30 from an inlet 170 and discharged through an outlet 180. Preferably, the reactive gas used is a deuterium gas (for D-D reactions) or a mixture of deuterium and tritium gas. However, any other fusionable mixture, such as D-^{3}He, may be used without departing from the present invention.

The outlet 180 is connected to a removable means for reducing the gas pressure 185 in the cylindrical vacuum chamber 30. In the test model, the removable means for reducing the gas pressure 185 is a turbo vacuum pump 190. Preferably, the cylindrical vacuum chamber 20 is initially pumped down to 10^{-7} Torr pressure by the turbo vacuum pump 190 and then backfilled with gas to 10^{-4} Torr. Other pressures may be used without departing from the present invention. However, as is well known to those skilled in the art, pressure varies with the voltage and the distance between the cathode and the anode. Thus, if the pressure is changed, either the voltage or the distance between the cylindrical cathode 160 and the cylindrical anodes 90 and 100 or both must be changed as well.

The reactive gas may either be slowly fed into the chamber with the turbo vacuum pump 190 valved down and running such that the desired pressure is maintained after the gas is added, or alternatively the cylindrical vacuum chamber 30 may be sealed off with the contained gas at the desired pressure and the turbo vacuum pump 190 removed, as is discussed later. For long life operation of the sealed cylindrical vacuum chamber 30 configuration, special precautions to maintain gas pressure and purity, such as getters and internal gas reservoirs used in other sealed tube electronic devices, may be employed.

A means for applying an electric potential 200 between the cylindrical anodes 90 and 100 and the cylindrical cathode 160 and the concave reflecting dishes 130 and 140 is supplied. In the test model, the means for applying an electric potential 200 is a positively-biased, high voltage power supply 210 connected by feedthroughs 220 and 230 attached to connectors 240 and 250 extending through the wall of the cylindrical vacuum chamber 30 to the cylindrical anodes 90 and 100. However, other means for supplying an electric potential may be used without departing from the present invention.

The means for applying an electric potential 200 may supply one of two types of current: (1) a steady state current or (2) a pulsed current. The remainder of this description discusses the operation of the neutron/proton source 10 using a means for supplying an electric potential 200 that supplies a steady state current. However, a pulsed power supply may be used to obtain similar neutron yields as are achieved with steady state currents, but using less power. Preferably, a high voltage, low current steady-state power supply is first used to maintain a plasma discharge. A pulsed power supply connected to the appropriate electrodes then supplies pulses of current to the electrodes. This operation, as opposed to pulsing from a cold neutral gas condition, helps prevent arcing and enhances the ability to maintain a relatively constant voltage while the current is pulsed.

In one embodiment, the pulsed power supply is a unit composed of a capacitive storage with a fast switch. In the test model, a 2-μF capacitor was employed with a switch comprising a hydrogen thyration triggered by an SCR-capacitor circuit. However, other pulsed power supplies may be used without departing from the present invention.

The advantage of the pulsed power supply is that due to the current squared (or higher power) scaling of neutron yield, as is discussed below, pulsed operation provides an improved neutron yield per time averaged input power. This principal is best illustrated by

way of an example. Assume a 10^9 n/s yield for D-D reactions is achieved using 100 kV of voltage and a 15 mA current, i.e. 1.5 kW, steady state current input power. Switching to a 10 Hz pulse rate using 10 μsec wide pulses with a peak pulse current of 15 A provides a larger peak neutron rate, but the same 10^9 n/s time averaged rate calculated on the basis of I^2 scaling of the neutron rate during the pulse. However, this operation uses a time averaged input power of 100 kV x 15 A x 10^{-4} = 0.15 kW, where 10^{-4} represents the duty cycle, i.e. the fractional time that the pulses are "on." Thus, the average power requirement is reduced by a factor of ten by using the pulsed power supply.

The improvement in power efficiency with pulsed operation increases as the pulse width is decreased. The repetition rate is increased and the duty cycle is decreased so as to achieve the maximum peak current during a pulse. The pulse width in time must, however, be longer than the ion recirculation time in order to preserve good ion confinement. The recirculation time, in turn, depends on the geometry of the neutron/proton source 10 and the operation conditions. The recirculation time for the test model operating under typical conditions is of the order of five (5) μsec. Thus, the ten (10) μsec pulse width used in the example above meets the parameters established for the test model. Large variations in the recirculation time may occur, however, without departing from the present invention.

In addition to the improved power efficiency achieved by the pulsed operation, a pulsed neutron source is desired for certain applications of the neutron/proton source. For example, some neutron activation analyses utilize measurements of characteristic decay gamma rays emitted from short half-life isotopes created when the pulse of neutrons irradiates the sample being investigated.

In operation using a steady state power supply, the cylindrical vacuum chamber 30 is initially evacuated to a low pressure by the turbo vacuum pump 190, and then backfilled with

gas. Next, high positive voltage is biased to the cylindrical anodes 90 and 100. The gas pressure used depends on the operation voltage. This high voltage will cause gas breakdown, separating ions from electrons in neutral atoms. The separated ions and electrons are then accelerated by the cylindrical cathode 160 and cylindrical anodes 90 and 100 in opposite directions in the direction of the electric field created by the high voltage bias. The electrons are accelerated towards the cylindrical anodes 90 and 100, simultaneously colliding with neutral atoms, thereby producing additional electron-ion pairs. The electrons then oscillate within the positive potential wells created by the cylindrical anodes 90 and 100 and the concave reflecting dishes 130 and 140, ionizing still more neutral atoms and forming electron microchannels that help focus the ion beams.

The ions, on the other hand, are accelerated towards the cylindrical cathode 160, reaching maximum speed as they travel through the cylindrical cathode 160. After exiting the cylindrical cathode 160, the ions are decelerated and eventually reach a full stop before reaching the cylindrical anodes 90 and 100. Immediately following the full stop, they are accelerated again in the reverse direction toward the cylindrical cathode 160. In this fashion, the ions oscillate back and forth along electric field lines many times until they are scattered out of the system by interparticle collisions. The ions are also forced into ion beams by the electron microchannels, further raising the neutron yield.

During this oscillation, the ions reaching a sufficiently high speed will collide and fuse with neutral atoms and with other oscillating ions, producing neutrons. At the same time, the ions ionize background gas, producing secondary electrons. These electrons follow the same pattern as the electrons previously discussed. If deuterium gas is used, energetic neutrons are produced by D-D fusion reactions. If a mixture of deuterium and tritium gas is used, energetic neutrons are produced by D-T fusion reactions. Non-fusing ions either scatter or charge-exchange and eventually escape. The applied voltage, i.e. the ion speed, is selected to

be near the energy corresponding to the maximum fusion cross-section, generally 50-200 kV, or higher if appropriate electrical insulation is incorporated.

The neutron yield per unit power input of the instant invention is greater than prior devices of this type because of the electron confinement in the positive potential wells, low ion loss, and good recirculating ion beam focusing. The yield can be expressed by the equation $R \propto I^2$, where R is the neutron yield and I is the total recirculation ion-beam current. Experiments to date have achieved a neutron yield of 10^6 n/s for D-D fusion reactions (equivalent to 10^8 n/s for D-T reactions) using 60 kV and 20 mA. However, theoretical calculations indicate that for larger power inputs (i.e. 100 kV and 1.5A), the neutron yield can rise as high as 10^{13} neutrons/second for D-D fusion reactions, and 10^{15} neutrons/second for D-T fusion reactions. Voltages up to 200 kV may be used with the instant invention, the limit set by the space required to insert appropriate insulating materials, which prevent arcing. In operation, the user sets the voltage to achieve the maximum fusion cross section (i.e. 200 kV). Then, the user increases the current to achieve the maximum neutron yield. As discussed earlier, a pulsed power supply can achieve the same time averaged neutron yield as with a steady state power supply, but use less input power in the process.

Since fusion neutrons are emitted and little material intercepts them prior to leaving the chamber, a nearly monoenergetic source in energy is obtained, centered around 2.5 MeV if deuterium fill gas is used and 14 MeV if the deuterium, tritium mixture is employed. Due to the larger fusion cross section for deuterium and tritium, neutron emission rates for this device will be about two orders of magnitude higher than for an equivalent deuterium device with the same power input. However, the use of radioactive tritium poses the added complication of requiring radiation protection licensing for its use.

A neutron/proton source 10 with an alternate geometry, such as a rectangular geometry, may be employed without departing from the present invention. Likewise, the axial shape of the neutron/proton source 10 and its components may vary without departing from the present invention. For example, the cylindrical anodes 90 and 100 can have a larger diameter than the cylindrical cathode 160.

The neutron/proton source 10 can be used as a proton generator after two slight modifications to the neutron/proton source 10. First, the gas used is D-^3He, which produces high energy (approximately 14 MeV) protons and 3.5 MeV alpha particles. Next, the operating voltages are set slightly higher than that for the normal operation of the neutron/proton source 10 to approach the voltage equivalent to the energy at which the D-^3He cross section peaks. The proton emission rate, however, will be close to the 2.5 MeV D-D neutron rate for an equivalent device with the same input power because the cross sections of D-^3He and D-D are similar. This embodiment has the advantage that with straightforward changes in the gas and voltage, the neutron/proton source 10 can be used as 2.5 MeV or 14 MeV neutron source, or as a 14 MeV proton source.

For the purpose of producing the instant invention for sale to consumers, the cylindrical vacuum chamber 30 is initially evacuated to a low pressure, and then backfilled with gas. Next, the inlet 170 and outlet 180 are sealed airtight. The process of starting the fusion reaction within the cylindrical vacuum chamber 30 is then done by the purchaser of the instant invention. After the gas in the neutron/proton source 10 has been contaminated with impurities due to sputtering of materials, minute leaks and reaction products (after thousands of hours of usage), the neutron/proton source 10 may be shipped back to the manufacturer, who will again evacuate the cylindrical vacuum chamber 30, backfill it with gas, reseal the inlet 170 and the outlet 180, and send the neutron/proton source 10 back to the purchaser. The proton source would be handled in a similar fashion.

In an another alternate embodiment of the instant invention, as shown in Fig. 3, a means for generating a magnetic field in the axial direction 260 is attached to the outer wall 50 of said cylindrical vacuum chamber 30. For the test model, the means for generating a magnetic field in the axial direction 260 is a plurality of magnetic rings 270 encircling the outer wall 50 of the cylindrical vacuum chamber 30. Also for the test model, the magnetic rings 270 are permanent magnets with an outside radius larger than the inside radius of the cylindrical vacuum chamber 30. However, other magnets, such as electromagnets or superconducting magnets, and other dimensions may be used without departing from the present invention. The magnetic rings 270 are preferably placed next to one another with no distance between them in order to generate a uniform magnetic field 280. However, if the user wishes to save costs, the magnetic rings 270 may be spaced apart in order to use fewer rings.

The purpose of the magnetic rings 270 is to generate a magnetic field 280, which confines both ions and electrons in the radial direction. As a result, the loss rate of particles lost to the inner wall 40 of the cylindrical vacuum chamber 30 is reduced, thereby allowing for higher fusion reaction rates. The strongest magnetic field possible, given the practical problems of engineering the magnet into the system, is desirable. In the test model, the maximum field strength achievable using permanent magnets is approximately 4 Kgauss. However, other types of magnets may generate higher field strengths.

Two types of magnetic fields 280 may be used with the present invention. The first is a shear B-field 290, which is essentially a surface magnetic field lying next to the inner wall 40 of the cylindrical vacuum chamber 30 in the axial direction, enclosing the cylindrical plasma column (i.e. the ion and electron beams viewed macroscopically) . The shear B-field 290 has a large magnetic field gradient ΔB between the inner wall 40 of the cylindrical vacuum

chamber 30 and the cylindrical plasma column. The shear B-field 290 provides a deflection force acting on all charged particles moving into it. Thus, both electrons and ions are forced away from the inner wall 40 of the cylindrical vacuum chamber 30 in a radial direction toward the cylindrical plasma column, thereby creating more particle collisions, which increases the fusion reaction rate. The force acting on a particle in the radial direction may be expressed as $F_r = -\mu\Delta B$, where F_r is the force in the radial direction and μ is the magnetic moment for the particle, which is proportional to the magnetic field gradient and points inward towards lower magnetic fields and the cylindrical plasma column.

The shear B-field 290 prohibits charged particles from leaving the system up to a specified energy, E_o, determined by the strength of the shear B-field 290. The confinement improvement can be evaluated in terms of $\tau_{p\,loss}/\tau_{p\text{-}p}$, the ratio of the average time for a charged particle to be lost due to upscattering (i.e. interparticle collisions that send particles in the radial direction) up to energy E_o to the average scattering-collision time, the scale of which is equivalent to the confinement time by a pure electrostatic field. The ratio, as derived in R.H. Cohen, et al., Nuc. Fusion 20, 1421 (1980) and P.J. Catto, et al., Phy. Fluids 28, 352 (1985), may be expressed as $\tau_{p\,loss}/\tau_{p\text{-}p} \propto \exp(E_o/E_{r,ave})$, where $E_{r,ave}$ is the average particle energy in the radial direction. $E_o = 0$ when there is no magnetic confinement, and $\tau_{p\,loss}/\tau_{p\text{-}p} = 1$. With the shear B-Field 180 added, $\tau_{p\,loss}/\tau_{pp} > 1$, indicating improved confinement. Using the shear B-field increases the efficiency (i.e. reaction rates per unit power) of the invention by approximately a factor of 5 in typical operation.

The second magnetic field type compatible with this embodiment is a homogeneous B-field (not shown) , which is a magnetic field spread uniformly through out the cylindrical vacuum chamber 30 in the axial direction with a radial magnetic field gradient of zero. Instead of deflecting charged particles, the homogeneous B-field rotates the charged particles perpendicular to the homogeneous B-field, thereby slowing down the diffusion of particles,

which increases the fusion reaction rate. The geofrequency of the rotation can be expressed as $\omega = eB/m$, where B is the magnetic field strength. The radius of gyration is $p = v_r/\omega$, where v_r is the angular velocity of the particles. The ratio of the diffusion with the homogeneous B-field to the diffusion without the homogeneous B-field, as derived in R. Papoular, Electrical Phenomena in Gases, 91 (1965), may be expressed as $D_r/D_0 = 1/(1 + (\omega\tau)^2)$ for transverse (i.e. radial) diffusion, where τ is the time interval between two successive collisions. Thus, the confinement is improved by the factor of $(1 + (\tau eB/m)^2)$. The resulting improvement in efficiency appears to be less than for the shear B-field 290. This configuration can be desirable, however, for certain applications.

Claims

1. An electrostatic accelerated-recirculating fusion neutron/proton source, comprising:

an axially elongated hollow vacuum chamber having an inner and outer wall;

reflectors located at opposite ends of said vacuum chamber so that their centers lie on the axis of said vacuum chamber;

a cathode that is 100% transparent to oscillating particles within said vacuum chamber between said reflectors, defining a central volume and having thc same axis as said vacuum chamber;

anodes that are 100% transparent to oscillating particles, the anodes being located near opposite ends of said vacuum chamber between said reflectors and said cathode and having axes coincident with the axis of said vacuum chamber;

reactive gas in said vacuum chamber; and

means for applying an electric potential between said anodes and said cathode and said reflectors to produce ions from the reactive gas within said central volume.

2. The neutron/proton source of Claim 1, wherein said axially elongated hollow vacuum chamber is substantially cylindrical.

3. The neutron/proton source of Claim 1, wherein said reflectors are concave reflecting dishes and their concave surfaces face the center of said vacuum chamber.

4. The neutron/proton source of Claim 1, wherein said cathode is substantially cylindrical, solid and hollow.

5. The neutron/proton source of Claim 1, wherein said anodes are substantially cylindrical and hollow.

6. An electrostatic accelerated-recirculating fusion neutron/proton source, comprising:

a substantially cylindrical vacuum chamber having an inner and outer wall;

concave reflecting dishes located at opposite ends of said vacuum chamber so that their concave surfaces face the center of said vacuum chamber and their centers lie on the axis of said vacuum chamber;

a substantially cylindrical, solid, hollow cathode within said vacuum chamber between said reflecting dishes, defining a central volume and having the same axis as said vacuum chamber;

substantially cylindrical, hollow anodes located near opposite ends of said vacuum chamber between said reflecting dishes and said cathode, having axes coincident with the axis of said vacuum chamber;

reactive gas in said vacuum chamber; and

means for applying an electric potential between said anodes and said cathode and said reflecting dishes to produce ions from the reactive gas within said central volume.

7. The neutron/proton source of Claim 6 including removable means for reducing the gas pressure in said vacuum chamber.

8. The neutron/proton source of Claim 7, wherein said removable means for reducing the gas pressure in said vacuum chamber comprises a turbo vacuum pump removably connected to said vacuum chamber.

9. The neutron/proton source of Claim 6 wherein said vacuum chamber is made of a non-electrically conductive material.

10. The neutron/proton source of Claim 6, wherein said means for applying an electric potential comprises a positively-biased, high voltage power supply.

11. The neutron/proton source of Claim 10, further comprising feedthroughs that attach said anodes to said positively-biased, high voltage power supply.

12. The neutron/proton source of Claim 10, wherein said positively-biased, high voltage power supply provides a continuous or a fixed rate current.

13. The neutron/proton source of Claim 10, wherein said positively-biased, high voltage power supply provides a repetitive pulse current at a preset repetition rate.

14. The neutron/proton source of Claim 6, wherein said means for applying an electric potential applies a positive potential between 10 kV and 200 kV.

15. The neutron/proton source of Claim 6 wherein said reactive gas is deuterium.

16. The neutron/proton source of Claim 6 wherein said reactive gas is a mixture of deuterium and tritium.

17. The neutron/proton source of Claim 6 wherein said reactive gas is a mixture of deuterium and Helium-3.

18. The neutron/proton source of Claim 6, further comprising a means for generating a magnetic field in the axial direction attached to the circumference of said vacuum chamber.

19. The neutron/proton source of Claim 18, wherein said means for generating a surface magnetic field is a plurality of magnetic rings.

20. The neutron/proton source of Claim 19, wherein said means for generating a surface magnetic field is a plurality of permanent magnets.

21. The neutron/proton source of Claim 19, wherein said means for generating a magnetic field is an electromagnet.

22. The neutron/proton source of Claim 19, wherein said means for generating a magnetic field is a plurality of superconducting magnetic coils.

23. The neutron/proton source of Claim 18, wherein said magnetic field is effectively a surface magnetic field lying next to said inner wall of said vacuum chamber.

24. The neutron/proton source of Claim 23, wherein said surface magnetic field has a large magnetic field gradient extending into said vacuum chamber.

25. The neutron/proton source of Claim 18, wherein said magnetic field is a homogeneous magnetic field spread uniformly throughout said vacuum chamber.

26. The neutron/proton source of Claim 25, wherein said homogeneous magnetic field has a radial magnetic field gradient approaching zero.

27. An electrostatic accelerated-recirculating fusion neutron/proton source, comprising:

a substantially cylindrical, non-electrically conductive vacuum chamber;

two concave reflecting dishes located at opposite ends of said vacuum chamber so that their concave surfaces face the center of said vacuum chamber and their centers lie on the axis of said vacuum chamber;

a substantially cylindrical, solid, hollow cathode within said vacuum chamber between said reflecting dishes and defining a central volume;

substantially cylindrical, hollow anodes located near opposite ends of said vacuum chamber between said reflecting dishes and said cathode and having axes coincident with the axis of said vacuum chamber;

a turbo vacuum pump removably connected to the vacuum chamber;

a positively-biased, high voltage power supply; and

feedthroughs attaching said anodes to said positively-biased, high-voltage power supply.

28. The neutron/proton source of Claim 27, wherein said positively-biased, high voltage power supply provides a continuous or a fixed rate current.

29. The neutron/proton source of Claim 27, wherein said positively-biased, high voltage power supply provides a repetitive pulse current at a preset repetition rate.

30. The neutron/proton source of Claim 27, wherein said means for applying an electric potential applies a positive potential between 50 kV and 200 kV.

31. The neutron/proton source of Claim 27 wherein said reactive gas is deuterium.

32. The neutron/proton source of Claim 27 wherein said reactive gas is a mixture of deuterium and tritium.

33. The neutron/proton source of Claim 27 wherein said reactive gas is a mixture of deuterium and Helium-3.

34. The neutron/proton source of Claim 27, further comprising a means for generating a magnetic field in the axial direction attached to the circumference of said vacuum chamber.

35. The neutron/proton source of Claim 34, wherein said means for generating a surface magnetic field is a plurality of magnetic rings.

36. The neutron/proton source of Claim 35, wherein said means for generating a surface magnetic field is a plurality of permanent magnets.

37. The neutron/proton source of Claim 35, wherein said means for generating a magnetic field is an electromagnet.

38. The neutron/proton source of Claim 35, wherein said means for generating a magnetic field is a plurality of superconducting magnetic coils.

39. The neutron/proton source of Claim 34, wherein said magnetic field is effectively a surface magnetic field lying next to said inner wall of said vacuum chamber.

40. The neutron/proton source of Claim 39, wherein said surface magnetic field has a large magnetic field gradient extending into said vacuum chamber.

41. The neutron/proton source of Claim 34, wherein said magnetic field is a homogeneous magnetic field spread uniformly throughout said vacuum chamber.

42. The neutron/proton source of Claim 41, wherein said homogeneous magnetic field has a radial magnetic field gradient approaching zero.

Fig. 1

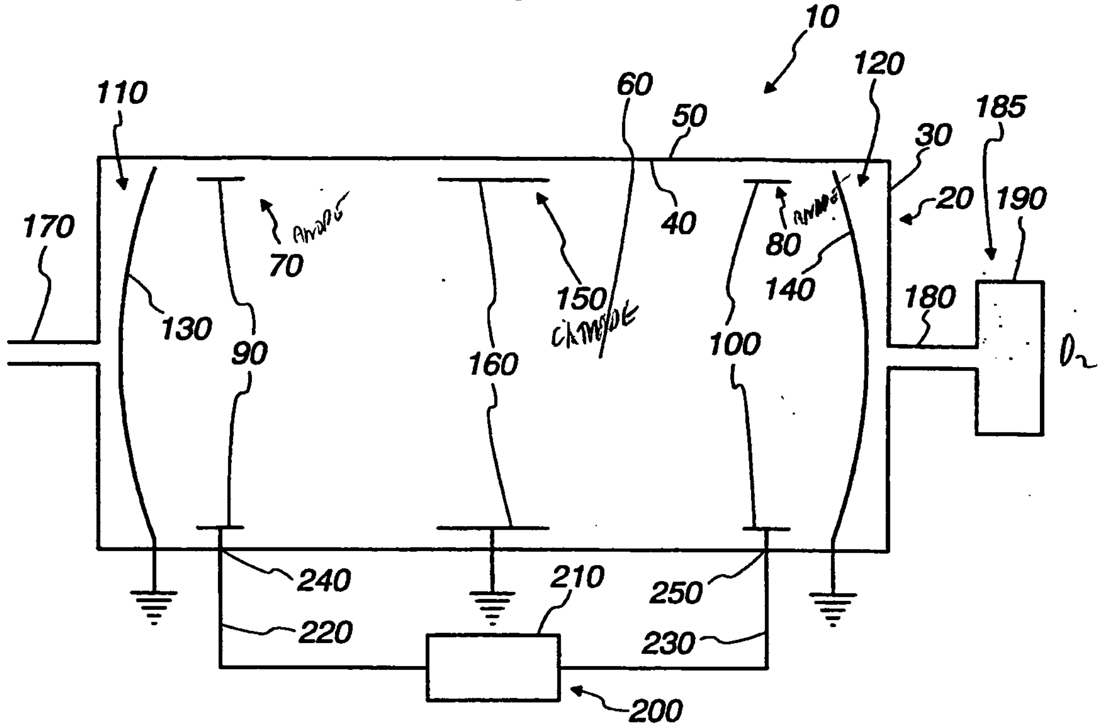
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Fig. 2

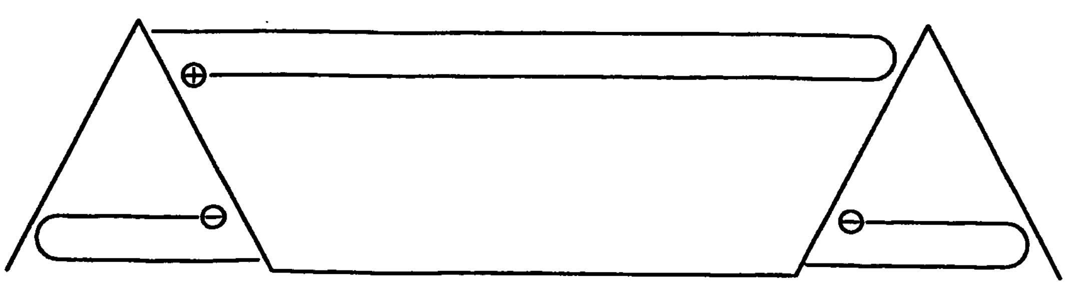
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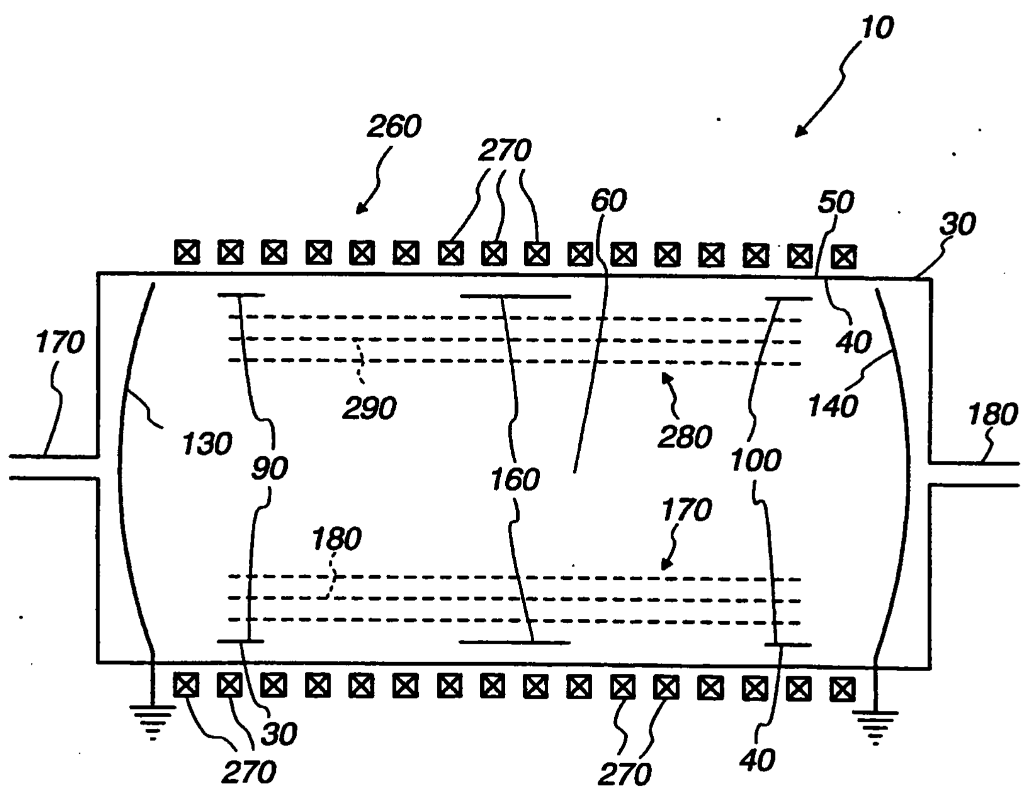
Fig. 3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